

# Validation of Interannual Differences of AIRS Monthly Mean Parameters

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## Abstract

Monthly mean fields of select geophysical parameters derived from analysis of AIRS/AMSU data, and their interannual differences, are shown and compared with analogous fields derived from other sources. All AIRS fields are derived using the AIRS Science Team Version 4 algorithm. Monthly mean results are shown for January 2004, as are interannual differences between January 2004 and January 2003. AIRS temperature and water vapor profile fields are compared with monthly mean collocated ECMWF 3 hour forecast and monthly mean TOVS Pathfinder Path A data. AIRS Tropospheric and Stratospheric coarse climate indicators are compared with analogous MSU products derived by Spencer and Christy and found in the TOVS Pathfinder Path A data set. Total ozone is compared with results produced by TOMS. OLR is compared with OLR derived using CERES data and found in the TOVS Pathfinder Path A data set. AIRS results agree well in all cases, especially in the interannual difference sense.

## 1. Introduction

AIRS/AMSU was launched on EOS Aqua in May 2002 as part of a mission to measure climate variability and trends. AIRS observations also provide data needed to improve operational forecast skill. To be an important component of a long term climate mission, AIRS products should be consistent with (and potentially more accurate than) those derived from other sources, at least in the interannual monthly mean sense. This consistency should apply to concurrent data sets, such as obtained using other satellite observations or analyses such as ECMWF or NCEP. In addition, it should apply to earlier data sets so as to be able to extend older climate records for a better assessment of trends. An example of such a data record is the TOVS Pathfinder Path A Data Set (Susskind et al., 1997) which covers the period January 1979 to April 2005.

Susskind et al. (2005) describe the algorithm used to analyze AIRS/AMSU data and produce accurate soundings in up to 90% fractional cloud cover. This algorithm, referred to as Version 4 of the AIRS Science Team algorithm, has been operational at the Goddard DAAC since April 2005. This paper shows differences of January 2004 and January 2003 monthly mean fields of geophysical parameters derived from analysis of AIRS/AMSU data using Version 4. Interannual monthly mean differences are compared to analogous results obtained using collocated 3 hour ECMWF forecasts and various satellite derived fields. In generating the AIRS monthly mean fields, only those soundings at a given level of the atmosphere, or at the surface skin, which pass the level dependent quality tests described in Susskind et al. (2005) are used. The procedures suggested by Susskind et al. (2005) for use in generating monthly mean fields are the ones used in this paper.

## 2. AIRS Temperatures

Trends and interannual variability of atmospheric and surface temperatures are important measures of the extent, if any, of global warming, and whether it may be the result of an increased Greenhouse effect due to increases in the concentrations of atmospheric trace constituents. Multi-year atmospheric analyses, such as done by ECMWF or NCEP, provide data sets that can be used to assess such trends. These data sets represent the best estimate of the atmospheric state using a combination of satellite observations and information generated by a general circulation model (GCM). Care must be taken with regard to a possible bias influenced by use of a GCM in production of these data sets. Independent satellite-only based data sets provide an important additional component to assess interannual variability and trends. Much use has been made of the trends of MSU2R and MSU4 (Spencer and Christy), representing coarse layer mid-lower tropospheric and mid-lower stratospheric temperatures respectively, in the study of global warming. Spencer and Christy's MSU2R and MSU4 are based wholly on MSU (and later AMSU) observations. Susskind et al. (1997) have produced the TOVS Pathfinder Path A data set, using products derived from analysis of HIRS2/MSU data on NOAA operational polar orbiting satellites, which covers the period 1979-2004. Susskind et al. (1997) also derive products analogous to MSU2R and MSU4 which are computed from the retrieved states using radiative transfer. The interannual variability and trends of the analogues of MSU2R and MSU4 computed from TOVS soundings, and included in the TOVS Pathfinder Path A Data Set, have been shown to closely match those derived by Spencer and Christy based on microwave observations. Analogues of MSU2R and MSU4 are derived from AIRS

soundings in an identical manner. Deriving products analogous to MSU2R and MSU4 from the detailed state of the atmosphere explains the contribution of trends of temperatures at different layers of the atmosphere to the coarse layer trends observed by Spencer and Christy.

## 2.1 Atmospheric Temperatures

In generating monthly mean fields of atmospheric temperatures, the appropriate level dependent quality flags as described in Susskind et al. (2005) are used. For temperatures at pressures 200 mb and lower (higher altitude), all soundings passing the Stratospheric Temperature Test are averaged. For atmospheric temperatures at all other levels, all soundings passing the Mid-Tropospheric Temperature Test are averaged.

Figure 1a shows the monthly mean field for January 2004 of 500 mb temperature derived from accepted AIRS/AMSU retrievals. Monthly mean fields containing only AM and PM overpasses are generated separately and then averaged together with equal weight to produce the monthly mean field. Figure 1b shows the difference between the AIRS retrievals and the collocated ECMWF 3 hour forecast 500 mb temperatures. All AIRS products are derived and shown on a  $1^\circ \times 1^\circ$  latitude-longitude grid. White indicates agreement to within 0.5K, with each color interval corresponding to differences increasing by 1K (0.5–1.5, 1.5–2.5, etc.), with shades of red meaning AIRS is warmer. The global mean difference between AIRS and ECMWF 500 mb monthly mean temperature is  $-0.01\text{K}$  and the spatial standard deviation is  $0.45\text{K}$ . This is a positive and expected result, as the ECMWF forecast is very accurate at 500 mb. The largest differences occur at the highest latitudes, where AIRS retrievals are 0.5 to 1.5K cooler than ECMWF.

Figures 1c and 1d show analogous results for the difference of monthly mean 500 mb temperature between January 2004 and January 2003. Figure 1c shows significant interannual differences in monthly mean 500 mb temperatures, with a spatial standard deviation of 1.54K between the 2 months, and a global cooling of 0.36K in January 2004 compared to January 2003. Virtually identical features appear in the ECMWF forecast (not shown). Particular attention should be given to the areas near 45°N,150°W; 50°S,160°W; 50°S,40°W; 50°S,20°E; and 50°S,100°E; in which January 2004 was substantially warmer than January 2003.

The difference between the two interannual difference fields, shown in Figure 1d, indicates excellent agreement in global mean cooling (AIRS has larger cooling than ECMWF by 0.05K), spatial standard deviation (0.39K), and spatial correlation 0.97. The small spatially coherent differences in 500 mb temperature between AIRS and ECMWF in Figure 1b cancel out for the most part in the interannual difference field. This is reflected in the fact that the spatial standard deviation of the difference of interannual difference field is less than of the monthly mean field. We are investigating the cause of these small regional biases, which do not appear to be very significant in the interannual difference sense.

Figures 2a-2d show analogous results for 1 mb temperature, a level of the atmosphere at which ECMWF should be somewhat less accurate. AIRS is biased warm globally compared to ECMWF at 1 mb by 1.16K, and the spatial standard deviation between the two fields (2.62K) is significantly larger than it is at 500 mb. The monthly mean temperature differences between January 2004 and January 2003 are much larger at 1 mb than 500 mb, especially north of 60°N, with considerable cooling of more than 20K near the North pole. AIRS data shows a global cooling of 1.47K at 1 mb, with a spatial standard

deviation of 4.13K. AIRS agrees reasonably well with ECMWF in terms of global mean, standard deviation, and correlation, but the difference in the spatial standard deviation of the difference of AIRS from ECMWF is considerably larger than at 500 mb, at which ECMWF is globally more accurate. AIRS is most likely adding information at this level from the climate perspective. It should be noted that, as at 500 mb, the spatial standard deviation of the difference of the interannual difference fields is considerably less than of the difference of the monthly mean fields.

Table 1 shows analogous statistics for AIRS January 2004 global mean temperatures and differences of global mean temperatures between January 2004 and January 2003, as well as the difference between AIRS and ECMWF of the global mean interannual differences, the spatial standard deviation of the two interannual difference fields, and their correlation. Also included in Table 1 are analogous statistics comparing AIRS and TOVS Pathfinder interannual monthly mean differences for the same two months at those pressure levels for which monthly mean TOVS temperature profile are generated. The TOVS Pathfinder monthly mean temperatures have been adjusted to "what they would have been if observed at 1:30 AM, PM" in a manner to be described elsewhere.

Global mean interannual monthly mean temperature differences between January 2004 and January 2003 as retrieved from AIRS vary somewhat regularly as a function of height. There is cooling up to 200 mb, having a peak value in the region 400-500 mb, but being near 0.0K at 1000 mb and 200 mb. In the stratosphere, January 2004 is again cooler than January 2003, primarily in the region 70 mb to 50 mb and also at 1 mb. The magnitude of the biases in interannual global mean temperature differences determined from AIRS, and contained in the ECMWF 3 hour forecast, are generally less than 0.1K and are considerably

smaller than those of monthly mean temperatures themselves. This shows that the small regional dependent biases in monthly mean temperatures tend to cancel in the interannual difference sense at all levels of the atmosphere. The spatial standard deviations of the difference of interannual mean differences are also smaller than those of the monthly mean temperatures. Spatial correlations of the interannual mean differences found in each data set are very high, especially in the stratosphere, where the spatial standard deviation of the interannual mean differences are considerably larger than in the troposphere.

Interannual monthly mean temperature differences determined from AIRS data also show good general agreement with those found in the TOVS Pathfinder Path A data set, though mean and standard deviation of differences of AIRS from TOVS are considerably larger than AIRS from ECMWF, and the spatial correlations are poorer. This indicates that while AIRS data is more accurate than that derived from TOVS, as expected, it should be compatible with the older TOVS data set in terms of extending trends back to the period January 1979, covered by the TOVS Pathfinder Data set.

Figure 3a shows the interannual monthly mean difference of surface skin temperature derived from AIRS soundings. This field is constructed in a manner analogous to those shown in Figures 1c and 2c, except that over non-frozen ocean (referred to henceforth as “ocean”), only those cases passing the standard Sea Surface Temperature Test (Susskind et al., 2005) were used in generating the AM and PM monthly mean fields, while over land, sea-ice, and coasts (referred to henceforth as “land”), all cases passing the Mid-Tropospheric Temperature Test were used. To generate the monthly mean fields, monthly mean AM and PM fields were averaged together with equal weight, provided at least 5 observations during the course of the month were in each the AM and PM monthly mean

fields. In the event that this requirement is not met over land, those grid boxes are not included in either the monthly mean or interannual difference fields. Over ocean, AM and PM monthly mean temperatures are weighted together equally unless no observations are included in one of the cases. In this situation, the monthly mean value for the other time period is used. If no observations are found for either time of day, that grid point is not included in the monthly mean or interannual difference fields (note the data void in the area of preferential stratus cloud cover near 20°S, 10°E).

The spatial patterns of Figure 3a show some similarity to those of Figure 1c. Over ocean, the areas of warm anomaly for January 2004, mentioned above, also appear, though considerably weaker, in the surface skin temperature interannual difference field. The strong negative sea surface temperature differences near 30°S, 130°W and 30°S, 10°W are not well reflected in the 500 mb temperature difference field however.

Figure 3b shows the interannual difference of colocated surface skin temperature as included in the ECMWF 3 hour forecast field. The basic patterns in sea surface temperature interannual differences agree well, including the relative cooling of January 2004 compared to January 2003 at the equator between 120°W and 180°W. ECMWF land temperatures are less reliable for use as “truth”.

Figures 3c and 3d show the difference of the AIRS and ECMWF interannual difference field. Figure 3c shows that agreement over ocean is much better than over land. Figure 3d shows the difference of the interannual difference fields only over ocean 50°N-50°S. The color scale is twice as fine as previous scales, in that white represents  $\pm 0.25\text{K}$  and every color is an additional 0.5K. The spatial standard deviation is 0.51K and the correlation is 0.71. Some of the largest differences occur south of 40°S, where ECMWF

may be less accurate. It is interesting to note that while the warming in January 2005 near 50°S described previously shows up in the ECMWF interannual difference field, it is weaker than that found in the AIRS field. Significant negative differences are shown in Figure 3d near 45°N,50°W and 40°N,150°E that appear to be artifacts in the AIRS interannual difference field, as ECMWF should be accurate in these areas.

## 2.2 Coarse Climate Indicators

Spencer and Christy have been monitoring trends of lower-tropospheric temperatures and stratospheric temperatures from MSU observations in channels 2 and 4 to product products called MSU2R and MSU4, which have been shown to produce precise values of monthly mean anomalies (Spencer and Christy 1992, 1993; Christy et al., 2003). A value of MSU2R is generated in the middle of a scan line based on a linear combination of observations taken at different zenith angles across a scan line, with the implicit assumption that the scene does not vary across the scan line. MSU4 observations are generated at every MSU spot, using the observed value of MSU channel 4 adjusted to what it would have been if it were observed at nadir. These products are representative of integrals of temperatures through the atmosphere. MSU2R depends on the surface pressure and surface emissivity. For a 1000-mb surface with unit emissivity, MSU2R gets 21% of its radiance from surface skin emission, roughly 59% comes from the layer 1000-500 mb, 18% from 500-300 mb, and 2% from above 300 mb. MSU4 has 16% of its radiance coming from above 30 mb, 60% from 30-100 mb, and 24% from 100-300 mb.

AIRS values of products analogous to Spencer and Christy's MSU2R and MSU4 products are computed using radiative transfer based on the retrieved skin temperature,

microwave surface emissivity at 50.3 GHz, and temperature and moisture profile (Susskind et al. 1997). The methodology is identical to that used in generating the TOVS Pathfinder Path A data. Henceforth, analogues of MSU2R will be referred to as Tropospheric Coarse Climate Indicator (Tropospheric CCI) and analogues of MSU4 will be referred to as Stratospheric Coarse Climate Indicator (Stratospheric CCI).

To generate monthly mean values of Tropospheric CCI and Stratospheric CCI, values computed using AIRS retrievals that passed the Mid-Troposphere Temperature Test are averaged. Figures 4a-c show the interannual differences of Tropospheric CCI computed from AIRS and TOVS, and observed by Spencer and Christy. The Spencer and Christy product is derived on a  $2.5^{\circ} \times 2.5^{\circ}$  latitude-longitude grid. All three interannual differences show January 2004 to be colder globally than January 2003 by amounts ranging from 0.19K to 0.09K. The spatial standard deviation of the interannual differences are also indicated on the figures. Figure 4d shows the difference of the Tropospheric CCI interannual differences determined by AIRS and Spencer and Christy. Much of the features shown in Figure 4d are due to differences in spatial resolution, and AIRS interannual differences tend to be somewhat larger in magnitude than those found by Spencer and Christy. The biggest differences between AIRS and Spencer and Christy occur poleward of  $60^{\circ}\text{N}$  in the vicinity of the dateline. In these areas, AIRS shows little difference between January 2004 and January 2003, while Spencer and Christy show a warming on the order of 1.5K in January 2004 compared to January 2003.

Interannual differences of Tropospheric CCI are highly correlated with those of 500 mb temperature, shown in Figure 1c. The features at 500 mb are somewhat stronger, and have a larger spatial standard deviation, than those found in Tropospheric CCI, because

Tropospheric CCI responds to temperatures from the surface to 300 mb. It is interesting to note in Figure 1d that like AIRS, ECMWF shows no warming at 500 mb in the vicinity of the dateline north of 60°N.

The global mean interannual difference of Tropospheric CCI, 0.19K, is strongly influenced by the values of interannual mean differences from 700 mb and 400 mb, shown in Table 1, and also influenced (reduced) by contributions near the surface and at 300 mb. Interannual differences or trends of Tropospheric CCI should not be confused with (as they often are) differences or trends of surface air temperatures. They refer to two totally different phenomena. The AIRS global mean values and spatial standard deviation of Tropospheric CCI and Stratospheric CCI are included in Table 1, as well as relevant statistics related to interannual differences and the agreement of AIRS, Spencer and Christy, and TOVS. In the global mean sense, AIRS Tropospheric CCI best matches that of 600 mb temperature.

Figure 5a repeats the interannual difference of AIRS Tropospheric CCI, and Figures 5b-d show interannual differences of temperatures at 3 pressure levels that contribute significantly to Tropospheric CCI. The temperature at 500 mb, whose interannual difference is shown in Figure 1c, also contributes substantially to Tropospheric CCI. Patterns of these 5 interannual difference fields are similar to, but not identical with, each other. Note, for example, the five areas of local oceanic warming in January 2004 compared to January 2003 discussed previously. These patterns are clearly observed in all 5 fields, with a magnitude that increases with height until 500 mb and decreases higher altitudes. The patterns in Tropospheric CCI, and its global mean, are the result of a weighted average of those of the mid-lower tropospheric temperature profiles and surface skin temperatures.

Figures 6a-d shows interannual mean differences for Stratospheric CCI determined by AIRS, Spencer and Christy, and TOVS. Table 1 shows that in the global mean sense, Stratospheric CCI best matches that of the temperature at 50 mb. AIRS, Spencer and Christy, and TOVS all show global cooling of Stratospheric CCI in January 2004 compared to January 2003 with values of  $-0.42\text{K}$ ,  $-0.39\text{K}$ , and  $-0.30\text{K}$  respectively. Stratospheric CCI is sensitive to temperature changes from 100 mb to 10 mb, with peak sensitivity near 70 mb. Stratospheric CCI has a smaller global mean interannual difference than 70 mb because it is influenced considerably by surrounding temperature differences in the vertical. The spatial standard deviation is also smaller than those of temperatures at surrounding levels because of smoothing of out of phase spatial features in the vertical. The interannual difference of AIRS Stratospheric CCI agrees extremely well with that of Spencer and Christy, with a spatial standard deviation of  $0.36\text{K}$  and correlation of 0.99. The biggest difference occurs at the North Pole, where Spencer and Christy appears spuriously too low.

Figure 7a repeats the AIRS Stratospheric CCI, and Figures 7b-d show interannual differences of temperature at pressure levels contributing significantly to Stratospheric CCI. The global mean interannual differences of temperatures in the mid-lower troposphere vary dramatically as a function of height, with considerable cooling at 700 mb, and slight warming at 30 mb. The global mean Stratospheric CCI is of course an intermediate value influenced by changes at all the appropriate levels. These areas of warm sea surface temperature, discussed previously, appear prominently in Stratospheric CCI as negative interannual differences. The negative features in the southern hemisphere are largest at 70 mb, and then weaken with height. The northern hemisphere negative interannual

difference continues to magnify with height until 30 mb, but is not present at 10 mb (not shown).

### 3. Constituent Profiles

Version 4 of the AIRS Science Team algorithm generates vertical profiles of water vapor, ozone, and carbon monoxide in terms of layer column densities ( $\text{mol}/\text{cm}^2$ ) in 100 atmospheric layers. In generating monthly mean fields, the entire profile is accepted if the Constituent Test is passed. CO monthly mean fields will not be shown in this paper as we do not have another measure of this quantity to compare with.

#### 3.1 Water vapor profiles

Water vapor fields are presented in terms of total integrated water vapor column density above the surface, as well as above different atmospheric pressures. As with all derived products, water vapor profiles represent atmospheric water vapor in the clear portion of the partially cloudy scenes. It does not include water vapor above, within, or below clouds in the scene. Thus, there could be a sampling difference between derived water vapor fields and water vapor as predicted by forecast models, or as measured by microwave based observations, both of which would include water vapor in the cloudy portion of the scene.

Figures 8a and 8b show monthly mean total precipitable above the surface (cm) derived from AIRS/AMSU observations for January 2004, and the difference of AIRS monthly mean total precipitable water contained in the collocated ECMWF 3 hour forecast fields. The global mean AIRS total precipitable water for all cases passing the Constituent

Test (roughly 85% of all observations) is 2.42 cm. If tighter tests were used (see Susskind et al., 2005), sampling would eliminate most of the cloudiest cases, and less water vapor would result. We have tried to minimize a clear sky bias in monthly mean fields by including as many cases as possible. In a global mean sense, AIRS is moister than ECMWF by 0.17 cm (7.0%) with a spatial standard deviation of 0.16 cm (7.4%).

Figures 8c and 8d show analogous results for the interannual difference of total precipitable water between January 2004 and January 2003. Globally, AIRS shows 0.02 cm of precipitable water more in January 2004 than January 2003, or roughly 1% of the global mean value of 2.42 cm. This apparent “moistening” is probably within the noise of the measurement. The spatial standard deviation of the difference is 0.34 cm and is almost 15% of the global mean. Large spatially coherent differences exist, with considerable drying along the equatorial Pacific Ocean, and moistening in the tropical Atlantic and Indian Oceans and in the extratropical oceans. These features are in general correlated with interannual sea surface temperature differences. The relatively small negative sea surface temperature difference near the equator between 180°W and 120°W is accompanied by an extremely large drying in this and adjacent areas.

Figure 8d shows very good agreement with the ECMWF interannual difference of total precipitable water, with a spatial correlation of 0.94. The global standard deviation of the interannual difference of total precipitable water between AIRS and ECMWF is smaller than that of the monthly mean fields. This also indicates the existence of regional biases that tend to cancel when interannual differences are taken.

Figures 9a-d show analogous results for total precipitable water vapor above 500 mb ( $\text{mm} \times 10$ ). ECMWF values of water vapor in the upper troposphere are essentially model

driven and should be highly suspect. AIRS has a dry global bias of 0.053 mm compared to ECMWF (roughly 5% of the global mean) and the spatial standard deviation of the difference is 0.117 mm ( $\approx 10\%$ ). AIRS data indicates a drying of .015 mm above 500 mb (compared to a global mean of 0.996 mm) in January 2004, compared to January 2003 corresponding to 1.5% of the total. This result may be in the noise level of accuracy at this height of the atmosphere. The spatial standard deviation of the interannual difference is 40% of the global total, indicating a considerable redistribution of upper tropospheric water vapor between the two Januaries. The spatial pattern of interannual differences of upper tropospheric water vapor is similar to that of total precipitable water in some areas, but quite different in others. Note, for example, the region 120°E–180°E, 20°N–20°S. AIRS and ECMWF interannual differences agree closely, with a correlation of 0.95. These statistics, as well as analogous statistics for precipitable water above 850 mb, 700 mb, and 300 mb, are shown in Table 2.

### 3.2 Total O<sub>3</sub> burden

Because AIRS is an infra-red sounder, ozone profiles are produced day and night, as well as in polar winter. TOMS (Herman et al., 1991) produces highly accurate measurements of total ozone, but operates only under sunlight conditions because it is an ultraviolet based instrument. In generating AIRS monthly mean fields of total O<sub>3</sub>, all cases passing the Constituent Test were averaged, including both ascending (day) and descending (night) observations. The monthly mean AIRS total ozone field for January 2004 is shown in Figure 10a. The monthly mean TOMS ozone field, shown in Figure 10b, is the average of all TOMS daily fields, originally given on a 1.25° longitude by 1.0° latitude grid. We

generated the monthly mean TOMS total ozone field by averaging TOMS daily mean fields. The daily TOMS data was obtained from the website <http://toms.gsfc.nasa.gov/ftpimage.html>. At least 10 days of observations were needed for a given grid point to generate the monthly mean field. Figure 10c shows the difference between the monthly mean AIRS and TOMS total ozone fields for January 2004. Care should be taken about differences near the TOMS terminator, at about  $61^{\circ}\text{N}$ , because of possible time of month sampling differences.

There is a reasonable agreement between monthly mean AIRS and TOMS total ozone fields. The global mean difference is 3.44 DU (1.3% of the TOMS global mean) and the spatial standard deviation is 10.09 DU (3.7%). It is important to note that AIRS produces reasonable values of total ozone north of the terminator, where no TOMS data exists. It is clear that some large scale spatial systematic differences exist between the AIRS and TOMS fields. The cause of this needs to be understood.

Figures 11 a-c show analogous results for the difference of monthly mean total ozone between January 2004 and January 2003. Features of the interannual differences of total  $\text{O}_3$  are depicted well by AIRS. The spatially coherent differences have cancelled out to some extent, though AIRS appears to show a spurious increase in global total ozone by 5 DU. Over extratropical oceans, spatial patterns of interannual differences in total ozone are similar to, and in phase with, those of 70 mb temperature, which are in turn out of phase with those of surface skin temperature.

The spatial standard deviation of the difference of the interannual difference fields is 8.71 DU, compared to 10.09 DU for the monthly mean fields. It is encouraging to see a spatial correlation of 0.80 for the interannual difference fields where they both exist, and a

spatially coherent interannual difference field at high latitudes where TOMS data does not exist. We are examining the causes of the systematic differences between AIRS and TOMS and expect an improved O<sub>3</sub> retrieval algorithm in the next version of the AIRS retrieval algorithm to become operational at the Goddard DAAC.

#### 4. Outgoing Longwave Radiation (OLR) and Clear Sky OLR

OLR is computed using radiative transfer (Mehta and Susskind, 1999; Susskind et al., 2003), based on the retrieved state for each AIRS field of regard (3x3 array of AIRS fields of view). The relevant geophysical parameters are the surface skin temperature and spectral emissivity, the temperature-moisture ozone profile, and heights and amounts (radiatively effective fractional cloud cover) for up to 2 layers of clouds. As described in Susskind et al. (2005), if the Stratospheric Temperature Test is passed, the state used to compute OLR is based on the combined IR/MW retrieval. If the Stratospheric Temperature Test fails (primarily in cases of greater than 90% effective fractional cloud cover), then the microwave strat IR retrieval state is used, both to determine the cloud parameters and subsequently to compute OLR. Clear Sky OLR is also computed for every AIRS field of regard. The computation of Clear Sky OLR is analogous to that of OLR, but the 2 effective cloud fractions are set equal to zero. It represents the long wave flux that would have gone to space if no clouds were present in the field of view.

Spatial variability and trends of OLR are commonly used as possible indicators of factors related to the Greenhouse effect and global warming. Wielicki et al. (2003) have shown that trends of OLR determined from ERBE and CERES observations are similar to those found in the TOVS Pathfinder Path A data set, in which OLR is calculated in an

analogous manner to that used with AIRS data. AIRS (and TOVS) in principle adds nothing new to the OLR record determined by CERES, but can be used to explain the variability of CERES OLR in terms of variability of the component parts.

Figures 12 a-c show interannual differences of monthly mean OLR between January 2004 and January 2003 determined from AIRS, TOVS, and CERES respectively. The AIRS product is the average of the 1:30 AM and 1:30 PM local time observations. TOVS data has been "corrected" to what it would have been at 1:30 AM and 1:30 PM in a manner to be described elsewhere. The CERES product has been corrected to what it would have been if it were observed continuously over the whole day (Wielicki et al., 1998). Both AIRS and TOVS data are on a  $1^\circ \times 1^\circ$  grid, while the CERES data is on a  $2^\circ \times 2.5^\circ$  grid. The CERES data was obtained from the website [http://eosweb.larc.nasa.gov/HBDOCS/langley\\_web\\_tool.html](http://eosweb.larc.nasa.gov/HBDOCS/langley_web_tool.html).

AIRS shows a global lowering of OLR by  $1.01 \text{ W/m}^2$  in January 2004, TOVS shows a lowering by  $0.42 \text{ W/m}^2$ , and CERES shows a lowering by  $0.94 \text{ W/m}^2$ . There is excellent agreement of all three independently determined values. Figure 12d shows that the spatial standard deviation of the differences of interannual difference of OLR as observed by AIRS and CERES is  $3.95 \text{ W/m}^2$  and the spatial correlation is 0.92. Much of the discrepancy may be attributable to differences in spatial resolution. Note that the maxima of the interannual differences (positive or negative) are larger in AIRS than in CERES.

The excellent agreement in the interannual mean sense shows that AIRS products can be used to explain the causes of the variability of the CERES OLR. The agreement is also an indirect validation of the component AIRS products in an interannual difference sense. In the monthly mean sense, AIRS is  $7.75 \text{ W/m}^2$  higher than CERES, with a spatial

standard deviation of  $5.02 \text{ W/m}^2$ . The warm bias is spatially coherent, with a maximum near the equator and falling off to near zero at  $60^\circ\text{N/S}$ . We are examining the cause of this.

Figure 13 illustrates different factors affecting the interannual difference of OLR between January 2004 and January 2003. Figure 13a repeats Figure 1sa, showing the AIRS interannual difference in AIRS OLR itself. Differences in OLR are often attributed to differences in cloud cover, especially in the tropics. Figure 13b shows the interannual difference in clear sky OLR determined from AIRS data. This field is computed assuming no clouds in the scene. Therefore all features are due to combinations of changes in surface skin temperature and atmospheric temperature and humidity. In the tropics, figures 13a and 13b appear similar, but the scales on the figures differ by a factor of 3. Therefore, tropical differences in clear sky OLR (primarily due to changes in upper tropospheric water vapor) contribute about  $1/3$  to the interannual differences of OLR, and differences in cloud parameters contribute about  $2/3$ . Figures 13c and 13d show the interannual difference in precipitable water vapor above 300 mb and in cloud top pressure. Higher values of upper tropospheric water vapor (red) contributes to lower values of OLR (blue), as due lower values of cloud top pressure, that is, higher altitude clouds (red). In the tropics, these two phenomena are highly correlated, as areas containing higher clouds (more convection) have more upper tropospheric water vapor as well.

In the extra-tropics, the interannual difference of Clear Sky OLR again looks similar to that of OLR, but “darker”. This is because the changes in both are due primarily to changes in surface and atmospheric temperatures. Most of the lowering of the global mean OLR by  $1.01 \text{ W/m}^2$  in January 2004 comes from the  $0.72 \text{ W/m}^2$  lowering in clear sky OLR.

Note that the patterns in Clear Sky OLR interannual differences are very similar to those of surface skin temperatures shown in Figure 3a.

## 5. Cloud Parameters

The monthly mean retrieved AIRS cloud fraction and cloud top pressure have been validated indirectly, at least in the radiative sense, by the excellent agreement of OLR computed using AIRS products with that observed by CERES. We have also compared monthly mean AIRS cloud fraction and cloud top pressure with that derived using monthly mean Aqua MODIS data obtained from the website

[http://disc.gsfc.nasa.gov/daac-bin/MODIS/Data\\_order.pl?PRINT=1&AQUA\\_DATA=1](http://disc.gsfc.nasa.gov/daac-bin/MODIS/Data_order.pl?PRINT=1&AQUA_DATA=1).

Figures 14 a and b simultaneously depict monthly mean cloud fraction and monthly mean cloud top pressure for January 2004 derived from AIRS and MODIS data respectively. The results are presented in terms of cloud fraction in 5 intervals: 0-20%, 20-40%, etc., with darker colors indicating greater amounts of fractional cloud cover. These intervals are shown in each of 7 colors, indicative of cloud top pressure. The reds and purples indicate the lowest pressure (highest altitude) clouds, and greens, blues, and violets represent mid-level clouds, and the yellows and oranges, the highest pressure (lowest altitude) clouds. The global mean and spatial standard deviation of the fractional cloud cover is shown in the figure. It is apparent that MODIS shows considerably more clouds globally than does AIRS (67.9% compared to 43.1%). An examination of the colors also shows that MODIS clouds are at consistently higher pressure (lower altitude) than those of AIRS.

Figures 14c and 14d shows AIRS monthly mean cloud fraction minus MODIS monthly mean cloud fraction, and AIRS monthly mean cloud top pressure minus MODIS monthly mean cloud top pressure for January 2004. The relatively systematic differences in both cloud fraction and cloud top pressure are evident in these figures.

The AIRS effective monthly mean cloud fraction is 24.9% lower than MODIS, with a spatial standard deviation of 12.1%. In Figure 14c, white indicates areas in which the AIRS effective cloud fraction is between 30% and 20% lower than that of MODIS, and the first shades of blue and red show differences of  $\pm 10\%$  from this range. Areas in which AIRS has greater fractional cloud cover than MODIS are shown in shades of yellow. Most areas show differences that are white or in the first color, relatively independent of cloud top pressure. AIRS indicates larger (and most likely spurious) fractional cloud cover over deserts than does MODIS. AIRS also shows more cloud cover than MODIS over Antarctica.

The global mean AIRS cloud top pressure, weighted by fractional cloud cover, is 152 mb lower (higher clouds) than that of MODIS. In Figure 14d, white indicates AIRS cloud top pressure is between 175 mb and 100 mb lower than that of MODIS. The first shade of red (indicative of even lower pressure) and blue (lower pressure by smaller amounts) indicate further differences of 50 mb. Areas in which AIRS cloud top pressure is higher (lower altitude) than MODIS are shown in shades of yellow. The largest differences in cloud top pressure (red) occur in the tropics, but not in the areas of maximum convection over South America, Africa, and the equatorial region between 120°E and 180°E.

Figures 15a and 15b show zonal mean plots of AIRS and MODIS cloud fraction and cloud top pressure for each of January 2003 and January 2004. MODIS data extends only

to 67°N, because daytime observations are used to generate the MODIS cloud parameters. The general zonal mean structure is very similar in both figures. Zonal mean interannual differences are also similar in both the AIRS and MODIS data.

Figures 15c and 15d show the interannual difference of the zonal mean cloud fraction and cloud top pressure for January 2004 minus January 2003 derived from AIRS and MODIS. While the values of cloud fractions and cloud top pressure differ considerably between AIRS and MODIS, the interannual differences are very similar. More work needs to be done to explain the differences systematic differences between AIRS and MODIS monthly mean cloud parameters.

## 6. Summary

Monthly mean values of geophysical parameters for January 2004, derived from analysis of AIRS/AMSU data, and the interannual differences from their values for January 2003, have been compared with those obtained from other sources. Atmospheric temperature and moisture show good agreement with ECMWF values at the levels where ECMWF should be accurate. Interannual differences of sea surface temperature also agree well with ECMWF (with two exceptions) where ECMWF should be accurate.

Interannual differences of tropospheric and stratospheric Coarse Climate Indicators derived from AIRS retrievals also agree well with analogous products produced by Spencer and Christy and produced in the 25 year TOVS Pathfinder Data Set. AIRS and TOVS soundings can both be used to explain how changes in temperature at different levels in the atmosphere contribute to changes and trends in the Coarse Climate Indicator records produced by Spencer and Christy.

Interannual differences of OLR derived from AIRS products agree extremely well with those obtained by the CERES team, as well as with OLR derived from TOVS Pathfinder Path A products. This, on the one hand, indirectly validates the interannual difference of AIRS (and TOVS) retrieval products. More significant, however, is the ability of AIRS (and TOVS) retrieved parameters to explain the variability and trends of OLR in terms of variability and trends of its component parts.

Cloud parameters derived from AIRS data show significant differences from those derived from MODIS data, however. More research is needed to understand and evaluate the significance of these differences.

All AIRS results shown are derived using the AIRS Science Team Version 4 retrieval algorithm (Susskind et al., 2005). The Goddard DAAC began analyzing near real time AIRS/AMSU data, using the Version 4 algorithm described in Susskind et al., 2005, on April 1, 2005. The DAAC also began analysis of historical AIRS/AMSU data going back to September 1, 2002, using the Version 4 algorithm. Level 1B (radiances), Level 2 (spot by spot retrievals) and Level 3 (gridded) data is available. The Level 3 data is given on a  $1^{\circ} \times 1^{\circ}$  latitude-longitude grid, and averaged in 1 day, 8 day, and monthly mean segments, with ascending (1:30 PM local time) and descending (1:30 AM local time) orbits gridded separately. Examples of monthly mean fields are shown in this paper. Susskind et al. (2005) show examples of fields gridded on a daily basis. The data can be ordered at <http://daac.gsfc.nasa.gov/data/datapool/AIRS/index.html>. Collection 003 should be requested which has results derived using the Version 4 algorithm described in this paper. Collection 002 has results derived using an earlier algorithm (Version 3). These should not be used for scientific studies. Research is continuing to improve the AIRS/AMSU retrieval

algorithm. Version 5 should be made operational and delivered to the Goddard DAAC in 2006. At that point, all previous AIRS/AMSU data will be reanalyzed using Version 5.

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## Figure Captions

- Figure 1      a) AIRS monthly mean 500 mb temperature, averaging 1:30 AM and 1:30 PM overpasses, for January 2004. b) The difference between AIRS and collocated ECMWF 3 hour forecast monthly mean temperatures for January 2004. c) As in a) but for the interannual difference of January 2004 and January 2003. d) As in b) but for the interannual difference of January 2004 and January 2003.
- Figure 2      a-d) As in Figure 1 but for 1 mb temperature.
- Figure 3      a-c) As in Figure 1 a-c), but for surface skin temperature. d) As in Figure 3c but only over ocean 50°N-50°S latitude. The scale is twice as fine.
- Figure 4      Interannual difference of Tropospheric Course Climate Indicator. a) AIRS, b) TOVS, c) Spencer and Christy, d) AIRS minus Spencer and Christy.
- Figure 5      Interrannual difference of AIRS monthly mean temperatures affecting Tropospheric Course Climate Indicator. a) Tropospheric Course Climate Indicator. b) 850 mb, c) 600 mb temperature, d) 300 mb temperature.
- Figure 6      a-d) As in Figure 4, but for Stratospheric Course Climate Indicator.
- Figure 7      As in Figure 5, but for a) Stratospheric Course Climate Indicator, b) 70 mb temperature, c) 50 mb temperature, d) 30 mb temperature.
- Figure 8      a-d) As in Figure 1, but for total precipitable water.
- Figure 9      a-d) As in Figure 1, but for total precipitable water above 500 mb.
- Figure 10     a) As in Figure 1a, but for AIRS monthly mean total ozone. b) As in Figure 10a, but for TOMS total ozone. c) The monthly mean difference between AIRS and TOMS total ozone.
- Figure 11     a-c) As in Figure 10, but for the interannual difference of January 2004 and January 2003.
- Figure 12     As in Figure 4, but for OLR. a) AIRS, b) TOVS, c) CERES, d) AIRS minus CERES.
- Figure 13     As in Figure 5, but for OLR. a) AIRS OLR, b) AIRS Clear Sky OLR, c) AIRS precipitable water above 300 mb.
- Figure 14     a) Monthly mean cloud parameters derived from analysis of AIRS data for January 2004. Cloud height and cloud fraction are depicted simultaneously. Greater intensity of a color indicates more clouds

(0-20%, 20-40%, etc.). The color indicates cloud top pressure (red indicates high clouds; orange indicates low clouds). b) As in 14a but for MODIS monthly mean cloud parameters. Gray indicates no data. c) AIRS minus MODIS monthly mean cloud fraction. Yellow shows more AIRS clouds than MODIS. d) AIRS minus MODIS monthly mean cloud top pressure. Yellow shows higher pressure (lower altitude) AIRS clouds than MODIS.

Figure 15

a) Zonal mean AIRS and MODIS cloud fraction for January 2004 and January 2003. b) Zonal mean AIRS and MODIS cloud top pressure for January 2004 and January 2003. c) Interannual difference of AIRS and MODIS zonal mean cloud fraction. d) Interannual difference of AIRS and MODIS zonal mean cloud top pressure

Table 1

## Monthly Mean Temperatures (K)

January 2004							January 2004 – January 2003					
Pressure	AIRS		AIRS-ECMWF		AIRS		AIRS-ECMWF			AIRS-TOVS		
	mean	STD	mean	STD	mean	STD	mean	STD	corr	mean	STD	corr
1000 mb	287.42	11.06	0.53	1.15	-0.05	1.44	0.14	0.90	0.82	-0.02	1.24	0.45
850 mb	280.32	10.79	0.08	0.86	-0.09	1.69	0.04	0.71	0.93	-0.04	1.28	0.69
700 mb	273.23	9.95	0.31	0.51	-0.28	1.54	-0.05	0.45	0.97	-0.05	1.06	0.77
600 mb	266.27	10.00	0.40	0.43	-0.15	1.55	0.07	0.42	0.98			
500 mb	257.39	10.36	-0.01	0.45	-0.36	1.54	-0.05	0.39	0.97	-0.19	1.02	0.75
400 mb	246.02	9.99	-0.40	0.39	-0.45	1.50	-0.15	0.39	0.95	0.00	0.98	0.73
300 mb	232.58	8.35	-0.35	0.43	-0.10	1.33	0.03	0.46	0.94	0.02	0.85	0.83
200 mb	220.16	2.99	0.35	0.56	-0.06	1.99	-0.13	0.53	0.99	-0.60	0.98	0.92
150 mb	212.85	6.99	0.14	0.60	0.23	2.07	0.06	0.53	0.99			
100 mb	203.85	12.36	-0.46	0.64	-0.10	2.57	0.16	0.84	0.99	0.04	1.02	0.97
70 mb	204.96	11.04	0.26	0.80	-1.01	2.35	-0.21	0.81	0.99	-0.37	1.09	0.96
50 mb	209.95	7.71	0.22	0.79	-0.53	2.37	0.04	1.03	0.99	-0.29	1.12	0.95
30 mb	216.08	5.64	-0.17	0.67	0.10	3.05	0.09	0.91	0.99	0.54	1.39	0.90
10 mb	228.33	6.05	0.09	0.91	-0.06	2.74	0.02	0.72	0.99	0.15	1.67	0.81
1 mb	265.20	8.96	1.16	2.62	-1.47	4.13	0.26	1.76	0.99			

## Coarse Climate Indicators (K)

	January 2004		January 2004 – January 2003							
	AIRS		AIRS		AIRS-Spencer and Christy			AIRS-TOVS		
	mean	STD	mean	STD	mean	STD	corr	mean	STD	corr
Trop.CCI	267.59	11.20	-0.19	1.31	-0.10	0.72	0.81	-0.04	0.81	0.74
Strat.CCI	209.27	8.47	-0.42	2.00	-0.12	0.36	0.99	-0.03	0.66	0.97

Table 2

## Monthly Mean Precipitable Water above Pressure Levels (mm)

January 2004							January 2004 – January 2003					
Pressure mb	mean	AIRS		AIRS-ECMWF		AIRS		AIRS-ECMWF			AIRS-TOVS	
		STD	mean	STD	mean	STD	mean	STD	corr	mean	STD	corr
surf	24.18	15.88	1.75	1.83	0.21	3.44	0.01	1.19	0.94	0.57	2.63	0.71
850	11.94	8.39	0.95	1.17	0.05	2.51	-0.05	0.98	0.93	0.21	1.83	0.75
700	4.73	3.83	0.07	0.42	-0.08	1.45	-0.03	0.51	0.95	0.04	1.01	0.79
500	0.996	0.877	-0.053	0.117	-0.015	0.403	-0.014	0.132	0.95	0.037	0.289	0.81
300	0.0746	0.0551	-0.0074	0.0148	-0.0018	0.0239	-0.0037	0.0116	0.91	-0.022	0.0225	0.71

# 500 mb Temperature (K)

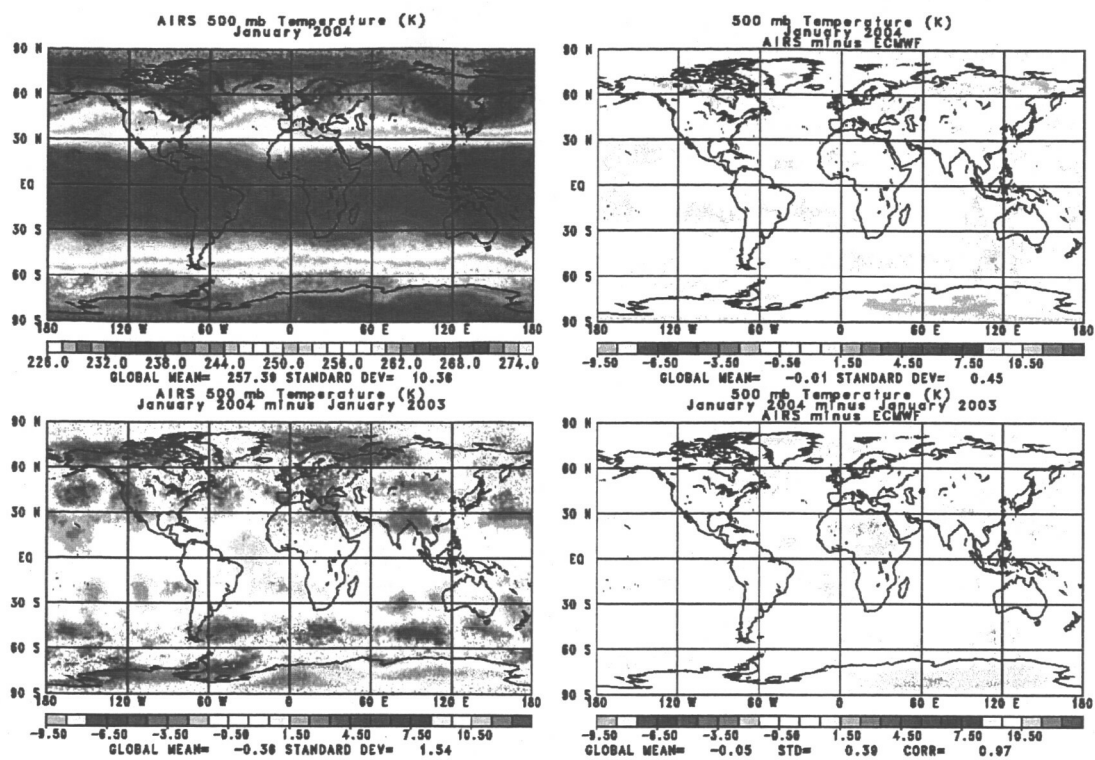


Figure 1

# 1 mb Temperature (K)

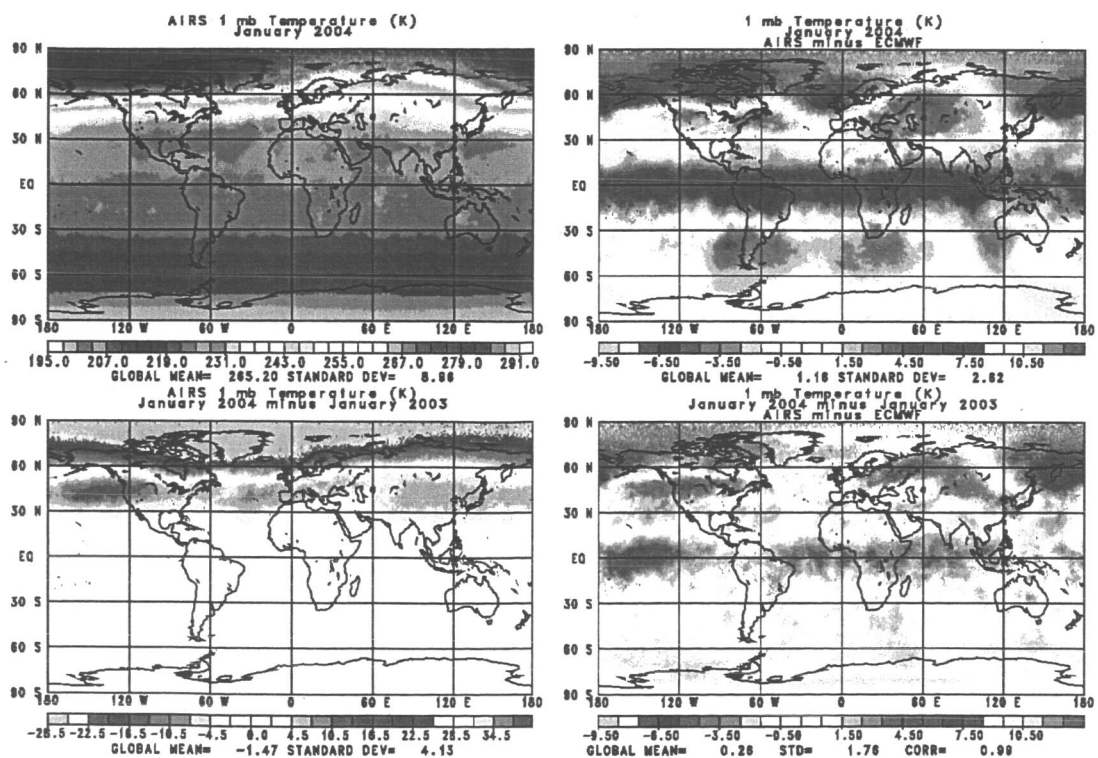


Figure 2

Surface Skin Temperature  
SST criteria over ocean  
Mid-Troposphere criteria over land

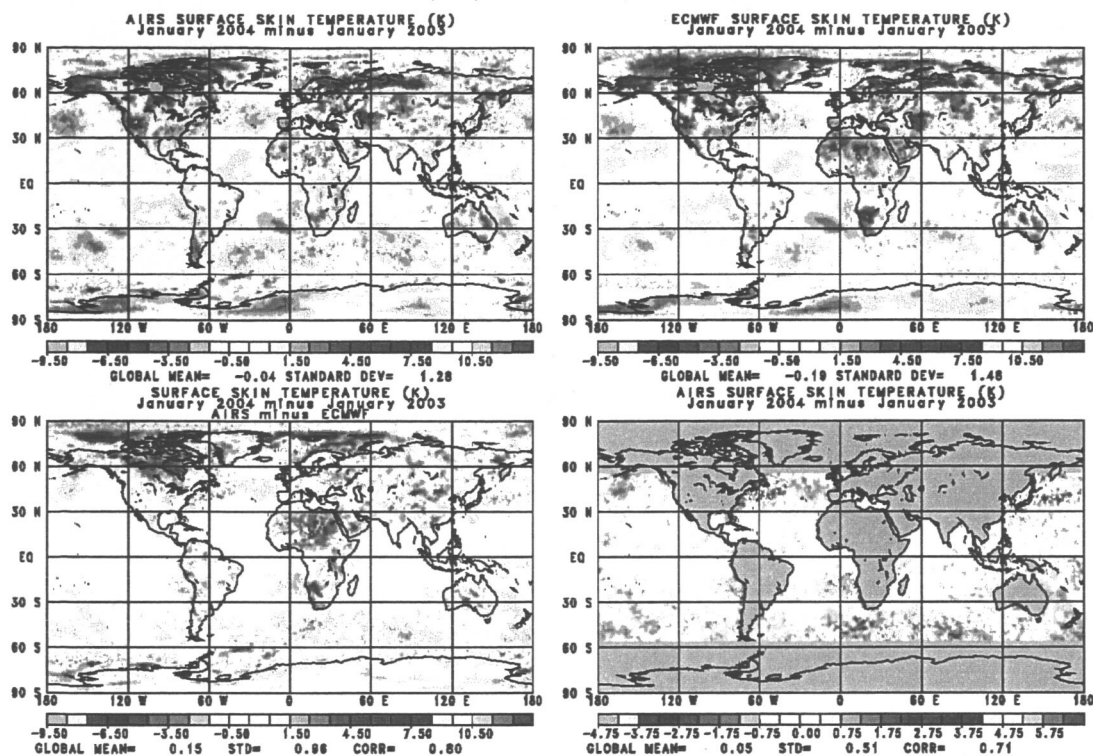


Figure 3

Trop CCI  
January 2004 minus January 2003

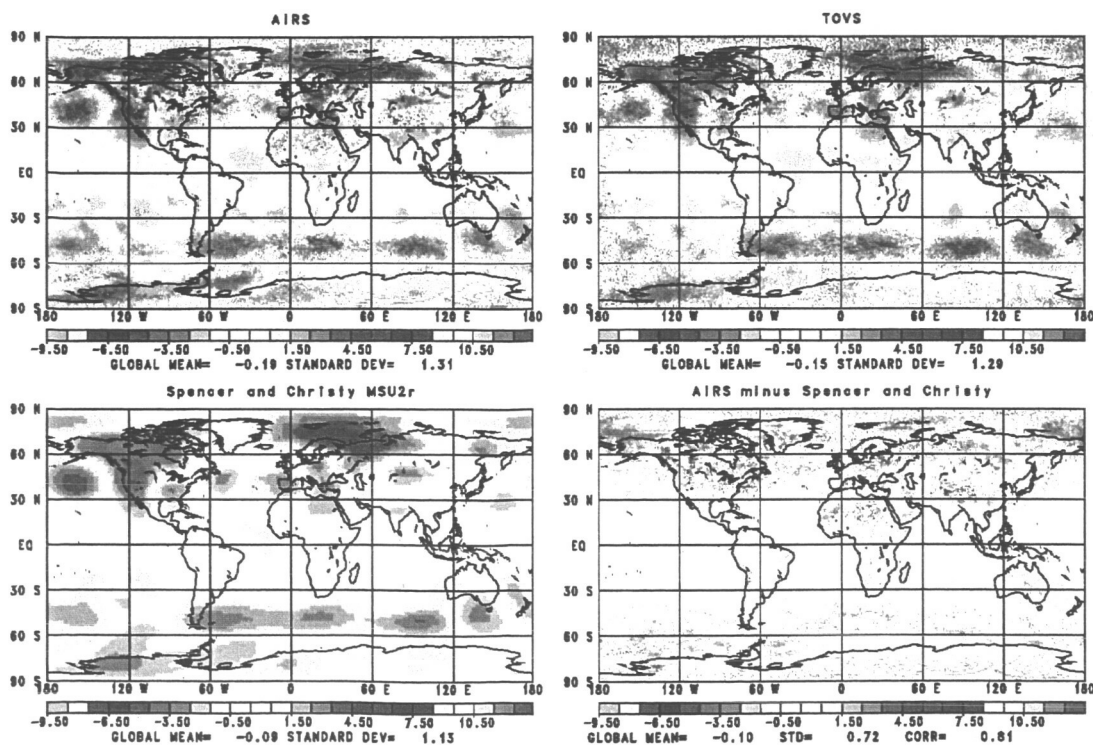


Figure 4

AIRS  
January 2004 minus January 2003

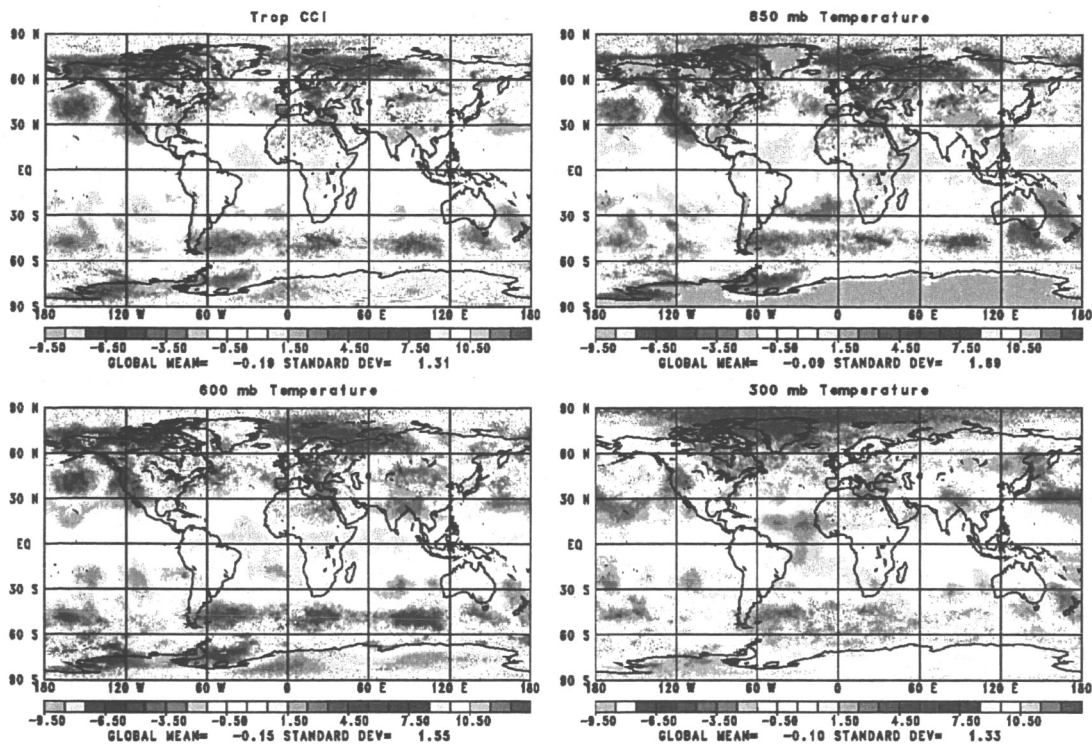


Figure 5

Strat CCI  
January 2004 minus January 2003

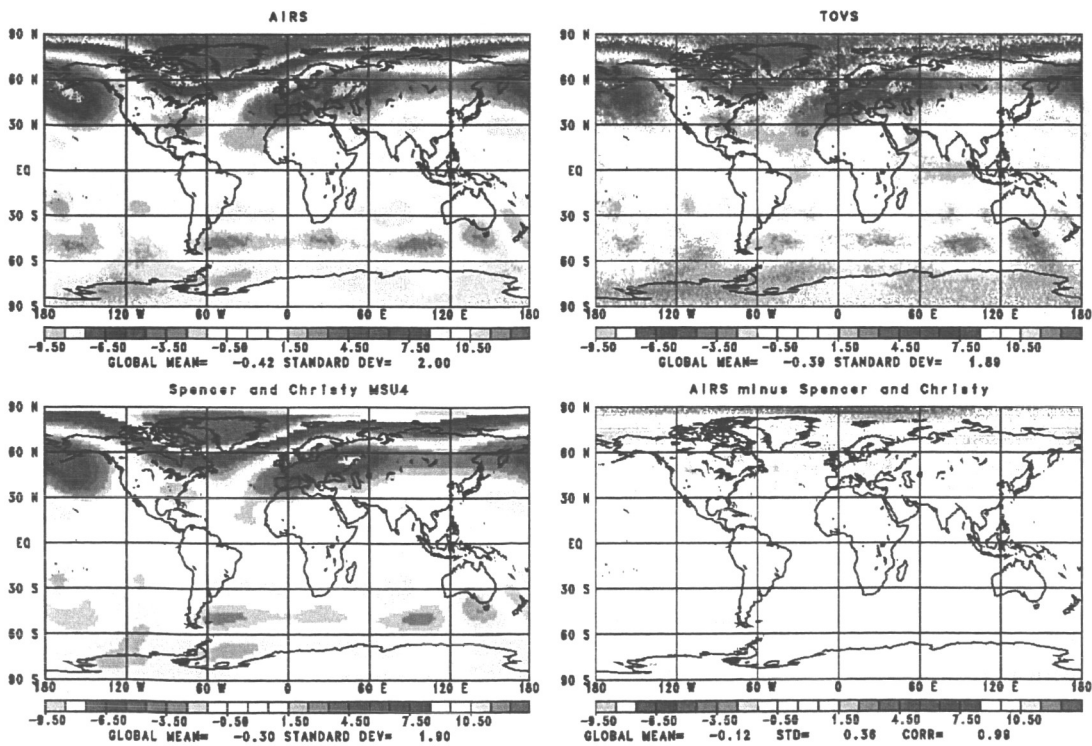


Figure 6

AIRS  
January 2004 minus January 2003

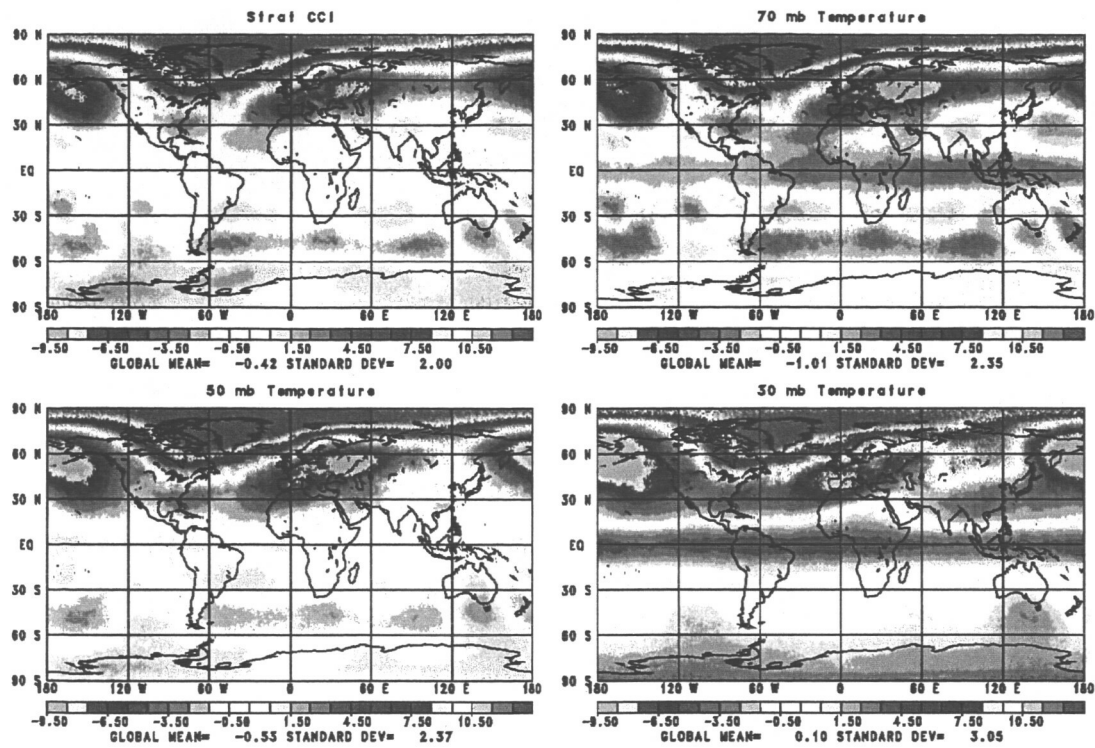


Figure 7  
Total Precipitable Water (cm)

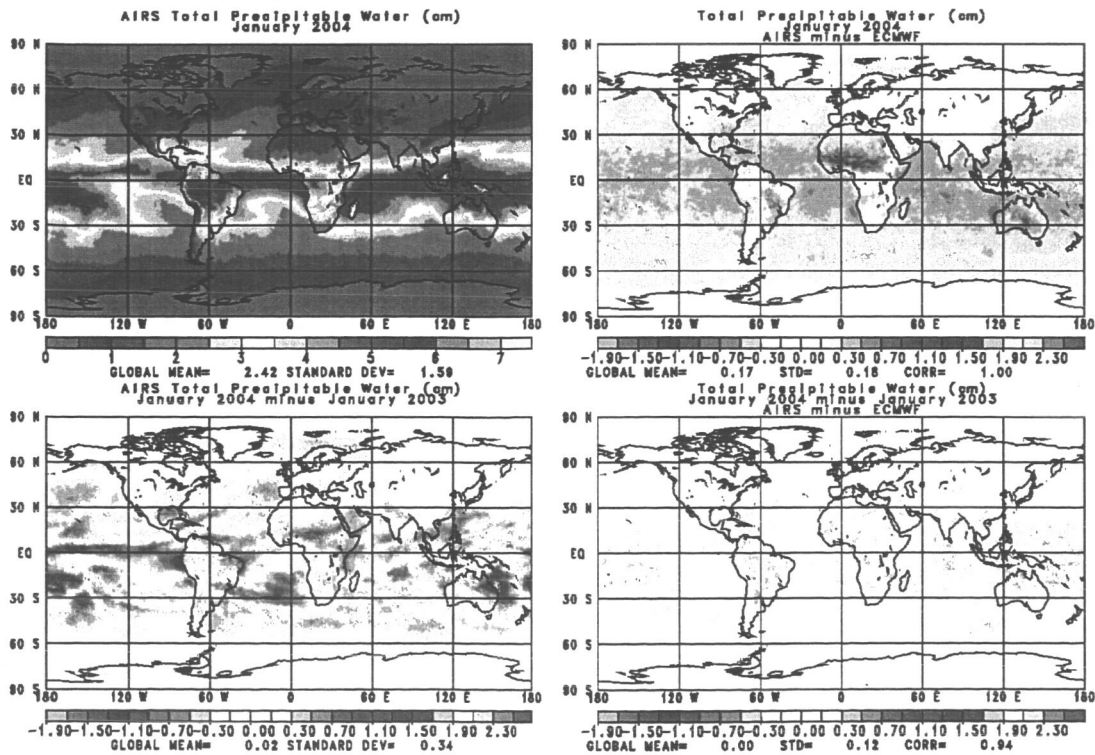


Figure 8

# Precipitable Water Above 500 mb (mm\*10)

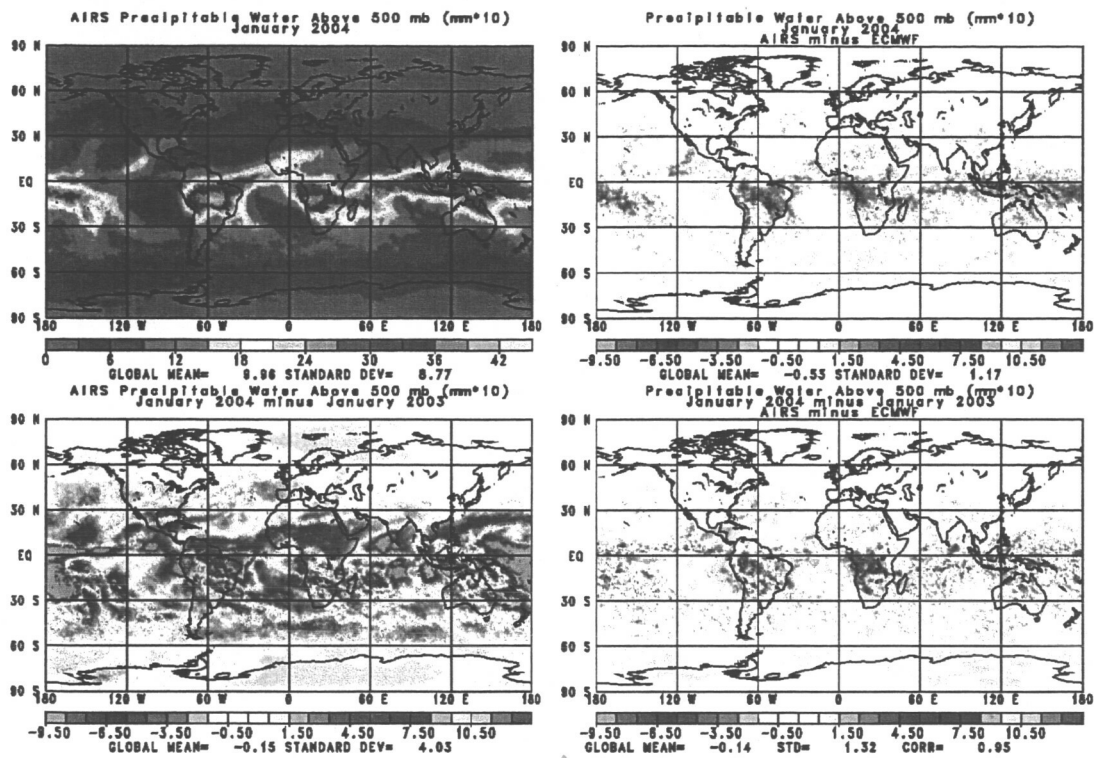


Figure 9  
Ozone (DU)

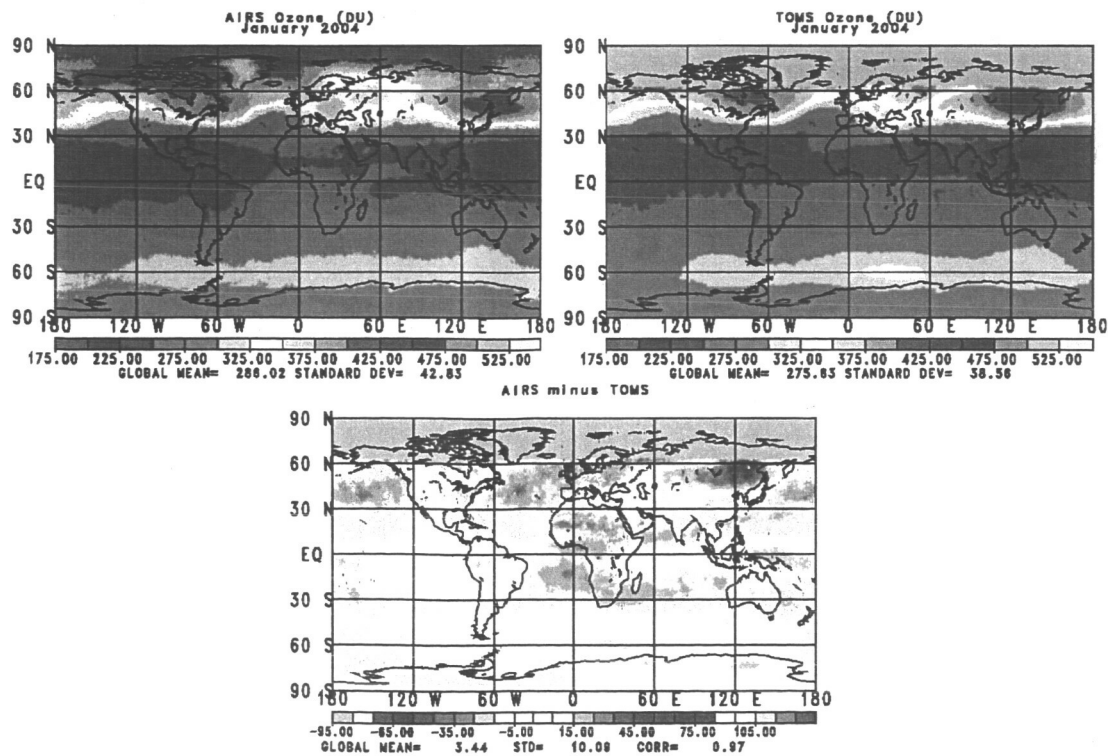


Figure 10

January Ozone (DU)  
January 2004 - January 2003

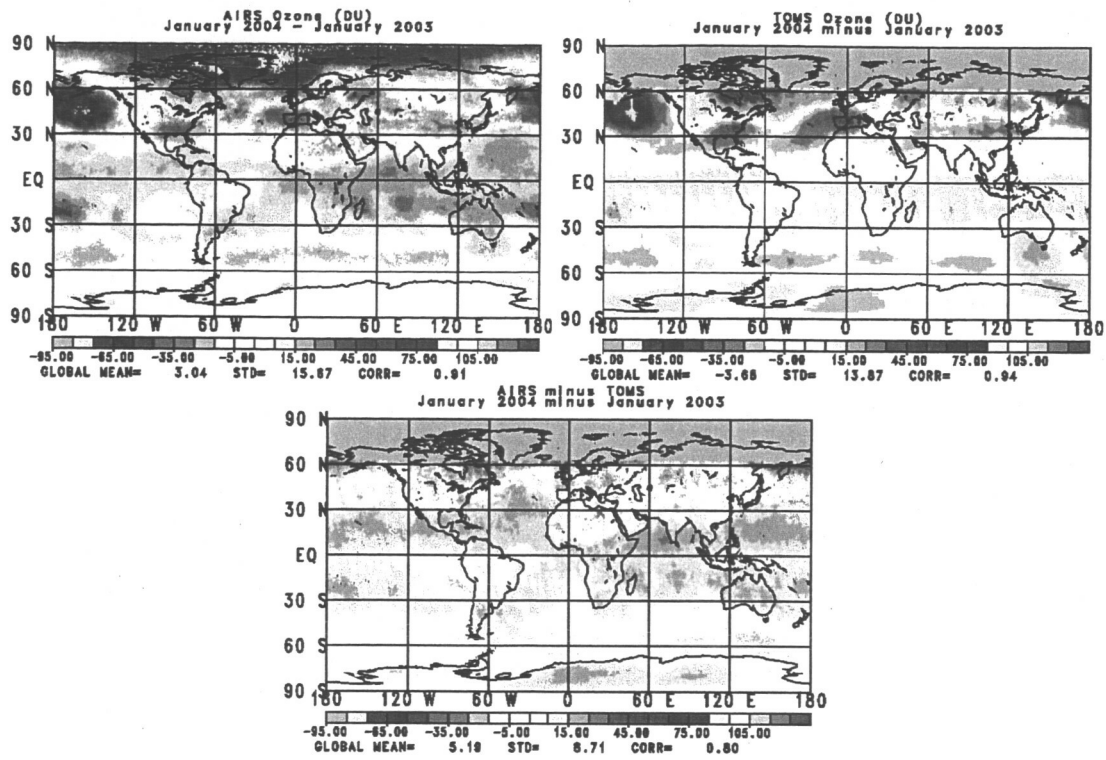


Figure 11  
Outgoing Longwave Radiation (watts/m<sup>2</sup>)  
January 2004 minus January 2003

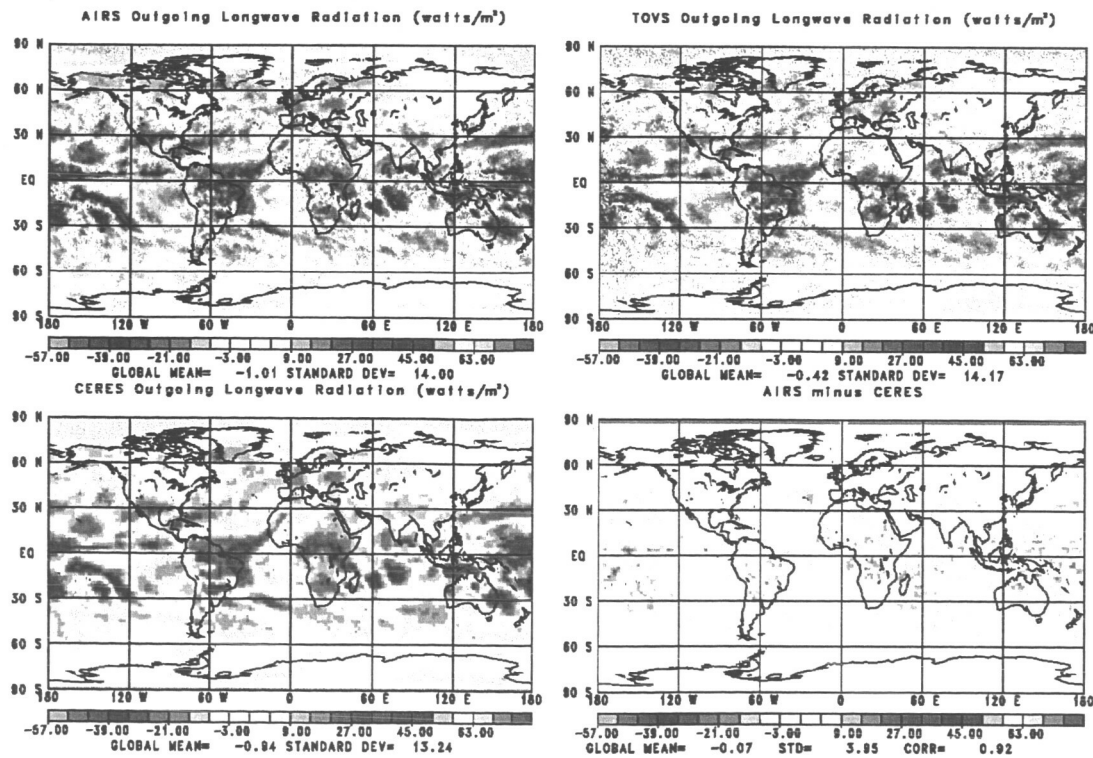


Figure 12

January 2004 minus January 2003

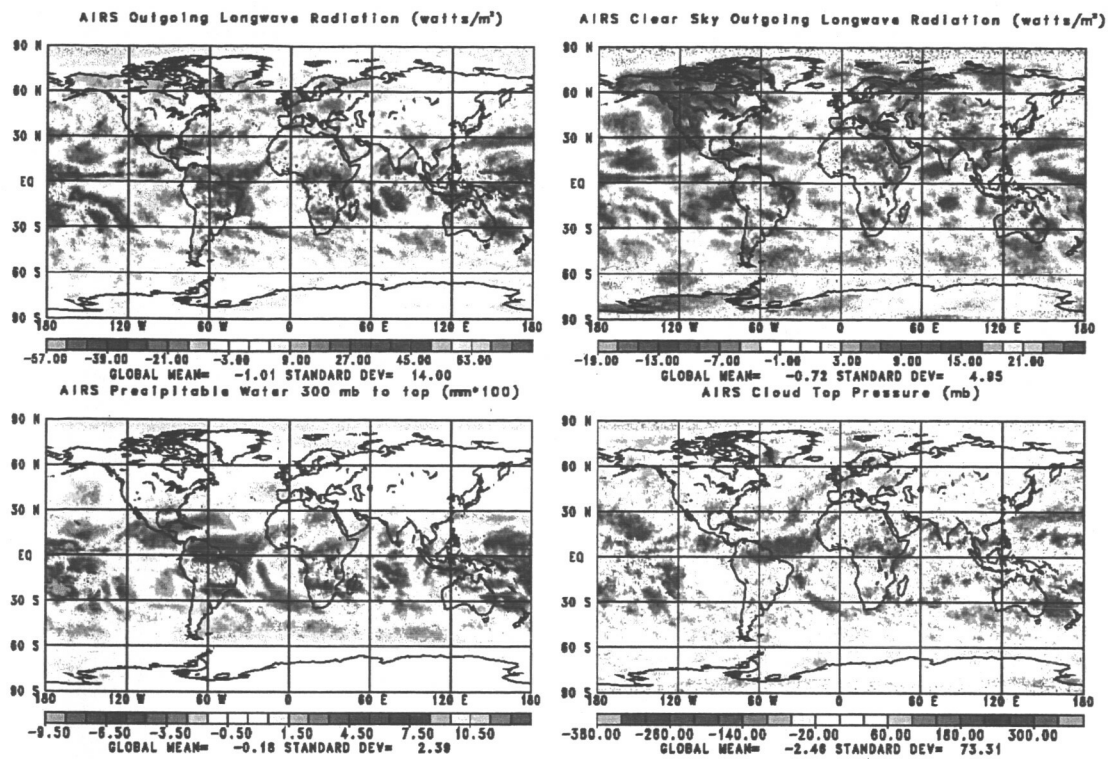


Figure 13

Cloud Parameters  
January 2004

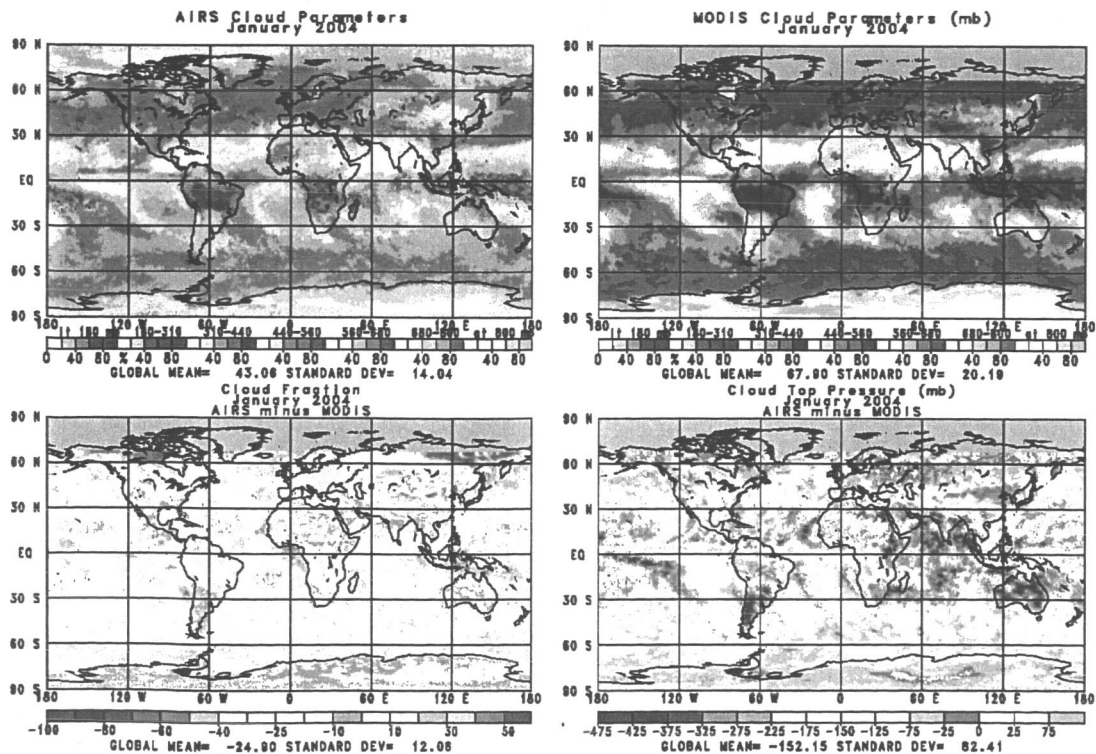


Figure 14

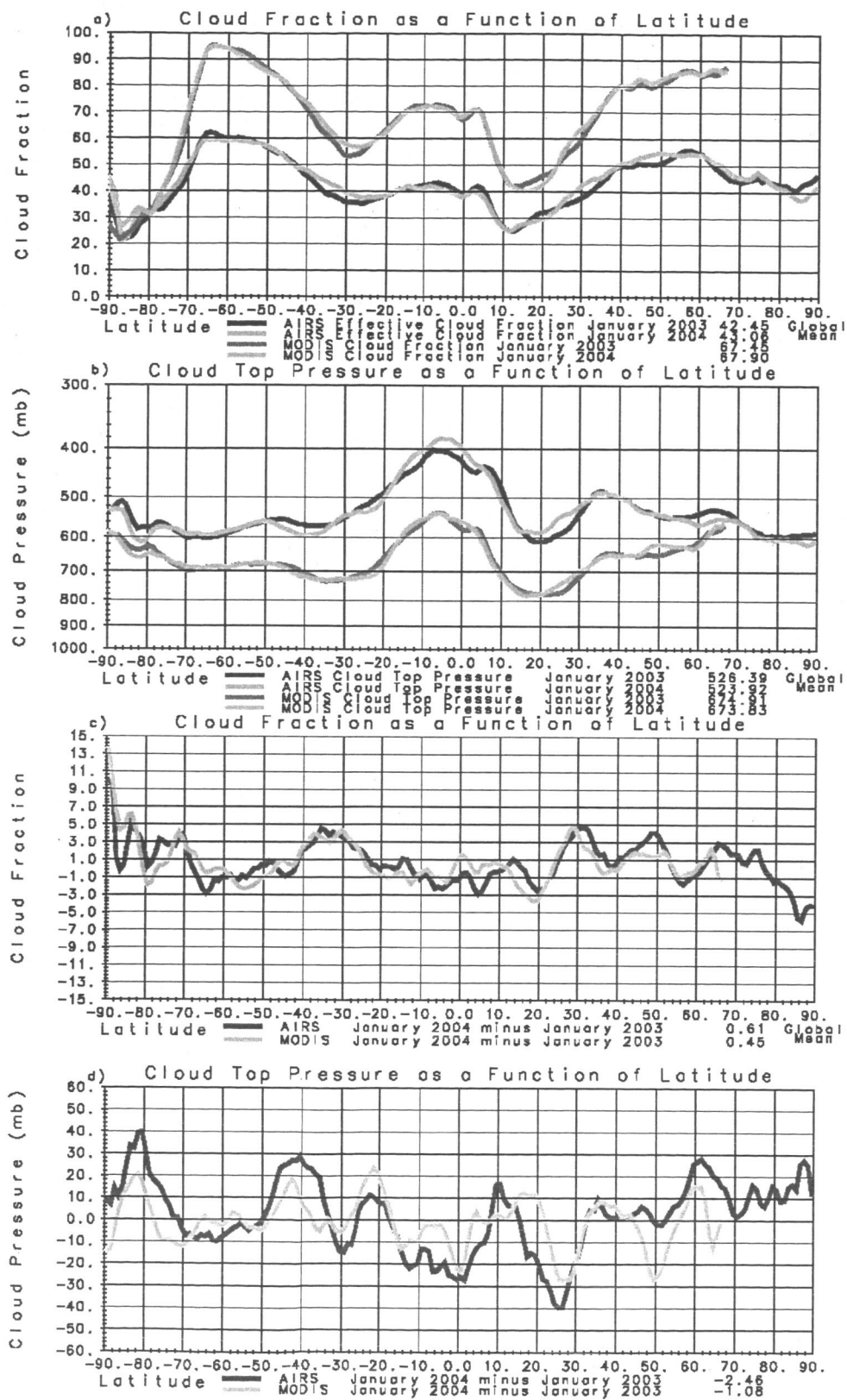


Figure 15